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The formation of tephra layers in peatlands

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ABSTRACT

Tephrochronology provides a valuable method of dating peat deposits but results may be compromised if tephra undergoes significant post-depositional movement. This study takes an experimental approach to investigate the processes of tephra taphonomy. Tephra was applied to peats and movement monitored over periods of up to six years. Experiments combined field studies on six British peatlands with rainfall simulation experiments in the laboratory. Tephra moved up to 15cm down through the peat but the vast majority remains at the surface at time of deposition, forming a layer which accurately records the palaeo-surface. Tephra moves both down, by shards sinking through the peat, and up, with shards being moved by plant growth or with water table variability. The extent of tephra movement probably depends on the density and porosity of the surface peat, there is no simple relationship with wetness. There is some indication that the extent of tephra movement depends on the tephra particle-size but this will require further work to confirm. Possible mechanisms of post-depositional tephra movement in peatlands are reviewed. The taphonomy of tephra is an important issue which should be considered in all studies of tephrochronology in peatlands.

KEYWORDS: Tephra, Cryptotephra, Microtephra, Peatlands, Mires, Bogs, Taphonomy

INTRODUCTION

Layers of volcanic ash are found preserved in sediments around the world. If the same tephra layer can be found in multiple sites it can provide a method of correlating the sequences (tephrostratigraphy). If the age of a tephra layer is known it can provide a means of determining the age of the surrounding sediments (tephrochronology). Tephrochronology provides a rapid and cost-effective alternative to radiometric dating for quaternary deposits. Many tephra layers are well-dated, either from the historical record or by dating programmes using approaches such as ^{14}C wiggle-matching. The precision of a tephra date can therefore often exceed that of a single radiocarbon date.

In recent years tephrochronology has been increasingly widely applied, primarily due to the more widespread use of cryptotephras, tephra layers composed of diminutive shards of volcanic ash which are not visible to the naked eye. As cryptotephra shards are so small and few in number cryptotephras can usually only be identified under the microscope. Cryptotephras are found at great distance from volcanic sources- Icelandic tephra has been recovered from the Netherlands (Davies et al. 2005) and Alaskan tephra from the Greenland ice cores (Pearce *et al*. 2004). Cyrptotephrochronology therefore expands both the geographical range of tephrochronology and the temporal range as microscopic methods increase the tally of identifiable tephras.

A key issue in tephrochronology is taphonomy. If the entire layer moves or if some of the tephra moves such that it is impossible to locate the isochron then the value of the method is undermined. In lake sediments these issues may be serious. Studies have suggested secondary deposition, biological mixing processes and density-related movement through the sequence (Anderson et al. 1985, Thompson et al. 1986, Boygle 1999, Beierle & Bond 2002). Concentration profiles are often complex (Davies 2007, Pyne-O'Donnell 2008). Many of these complicating processes may also affect marine tephra records (Ruddiman and Glover 1972).

Tephrochronology is widely used in peatlands but issues of taphonomy have received little consideration. There are several lines of evidence which suggest that the process's by which tephra becomes incorporated in peat are not always straightforward.

Enumeration of tephra shards to produce a concentration profile shows that there is not a simple layer of tephra but rather an extended zone in which shards may be found. This 'tail' of tephra distribution may stretch as far as 30cm (Gehrels et al. 2006). Some studies suggest that low concentrations of tephra may occur throughout the length of a core (Charman et al. 1995, Holmes et al. 1999).

Tephra profiles do not always show a simple monomodal distribution. Fig. 1 shows tephra shard concentration profiles from three tephras located during recent tephrostratigraphic research in southern Alaska (Payne et al. 2008). Fig. 1A shows a concentration profile with a simple, monomodal tephra distribution; there is a clear peak shard concentration and the tephra zone is closely confined. Fig. 1B shows a concentration profile with a small secondary peak; in this case the peak is minor representing just a few tephra shards and probably does not suggest any serious taphonomic issue. Fig. 1C shows a concentration profile in which tephra concentrations are high for a period of several centimetres. The concentration peak is not very pronounced and it is unclear where the isochron lies within this region. If the position of the isochron cannot be easily determined this greatly diminishes the usefulness of tephrochronology, particularly when fine chronological control is required.

Even where a simple tephra peak is present, it is not certain that this represents the palaeo-surface. In Iceland, Bjarnasson (1991) noted the sinking of a tephra layer through a moss carpet. Although, translocation of whole tephra layers seems unlikely it is a possibility which is difficult to exclude on the basis of palaeoenvironmental data. A related issue is lateral transport of tephra across the bog surface. Previous studies have noted differences in tephra occurrence and concentration between closely adjacent sites and even within sites (Payne 2008). Imaging studies of tephra layers have shown fine-scale horizontal variability in tephra layers (Dugmore and Newton 1992, Caseldine et al. 1999). If tephra is transported across the surface of peatlands this may serve to reduce the concentration of depleted regions to below the detectable limit.

A previous study investigated the taphonomy of tephra in a Scottish peatland using an experimental approach (Payne et al. 2005a). Tephra was applied to a number of plots and movement monitored over a period of two years. In all cases most tephra remained at the surface although some shards moved up to 6cm. This study was of a very limited scale with only three plots and the site is somewhat unusual because of the relatively dense, humified surface peats.

In this study we use an experimental approach to investigate the formation of tephra layers in peatlands, applying tephra to peats and monitoring its subsequent movement.

Key research questions are:

-Does the peak of a tephra concentration profile accurately represent the position of the mire surface at the time of deposition?

-Why are some tephra profiles irregular?

-Can tephra particle size provide a guide to the position of the isochron if the concentration profile is complex?

-To what extent does tephra move across the surface of a mire after deposition?

-What influences the movement of tephra down through the peat?

SITES and METHODS

To address these issues a combined field and laboratory experimental approach was employed. Both approaches have advantages: laboratory experiments allow closer control of environmental conditions and monitoring within a closed system, while field experiments allow more realistic simulations.

A first stage of experiments was designed to study the movement of tephra in an enclosed system over a short period of time, and specifically to study the impact of rainfall on tephra movement. Four peat blocks (34x36x17cm) were removed from *Sphagnum*-dominated lawn peat at Fox Tor Mires, Dartmoor, UK (grid reference SX6370) and placed in plastic containers with holes to allow drainage. Tephra was extracted from thick exposures of a grey, coarse-grained tephra believed to be over 1.63ma (B. Alloway pers. comm.) at Otoka Stream near Wanganui, New Zealand. Tephra was sieved at 400μm and applied to the peat blocks in layers 1mm (experiments RFS1a and RFS2a) or 5mm thick (experiments RFS1b and RFS2b). To allow an even application of tephra a layer of plastic mesh was placed over a layer of acetate sheet across the peat surface. The tephra was placed across the mesh and levelled out; the acetate sheet was then removed resulting in an even depth of tephra being deposited across the whole peat block. The tephra-treated blocks were subject to artificial rainfall in a laboratory rainfall simulator with UV lighting to maintain plant growth for 12 hours. Two rainfall intensities were used, 12 mm $hour^{-1}$ (experiments RFS1a and RFS1b) and 26 mm $hour^{-1}$ (experiments RFS 2a and RFS2b).

Peat blocks were allowed to drain and samples taken after 24 hours from the beginning of the experiments. Samples were extracted from two locations; in the centre of the block, and 40 mm from the edge to illustrate any variability. Sub-samples were taken through the full depth of the peat profile at either 10 mm, or 20 mm resolution where the peat would not allow more detailed sampling without disturbing the tephra. Samples were prepared for tephra analysis by ashing (Pilcher and Hall 1992). Peat sub-samples were dried at 105º C for 12 hours, weighed, incinerated at 700º C and then re-weighed. The remaining inorganic residue was washed in warm 10% HCl with a *Lycopodium* tablet added to allow shard concentrations to be enumerated (Caseldine et al. 1998, Stockmarr 1971). Slides were prepared with Hystomount and examined under the microscope at 400X magnification. Tephra shards were counted alongside at least 100 *Lycopodium* spores.

A second stage of experiments was designed to test the impact of tephra particle size on extent of tephra movement down through the peat in a field settting. Tephra in a full range of size classes was applied to plots in the Fenn's, Whixall and Bettisfield Mosses National Nature Reserve raised bog complex, spanning the English-Welsh border near Whitchurch in Shropshire (UK grid reference SJ4936). Three sampling areas were used in uncut sectors of the site; a lawn area of Bettisfield Moss (site 1), a hummock area of Whixall Moss (site 2) and a hollow area of Whixall Moss (site 3). These sites are collectively referred to as ‘Whixall’ hereafter. A full range of tephra sizes was used in these experiments. Different tephra sources were used for fine tephra (<300 μm) and coarser tephra (>0.5mm). The fine tephra was extracted from exposures near Kirkjubæjorklaustur in southern Iceland and is believed to represent the AD 1362 eruption of Őraefajökull (Ellershaw 2004, Payne & Blackford 2005a&b). Coarser tephra (ash and lapilli) was extracted from proximal deposits near Vesuvius (Italy) and probably derive from the 1944 eruption. Tephra was thoroughly washed and sieved. Seven size classes were applied: 3.35-4mm, 2-3.35mm, 1-2mm, 0.5-1mm, 150-300μm, 75-150 μm and <75 μm. Each size class was applied to two replicates on each of the three locations on the mire, giving a total of 42 applications (Table 1). The amount of tephra applied to each plot varied between 2 and 50g, dictated by the abundance of that size class within the extracted tephra samples.

Tephra was applied within a plastic ring (63mm internal diameter, 40mm depth) cut into the surface to contain the tephra within the sampling spot. Water was added to 'damp down' the finest (<150 μm) tephra; tephra application was followed by rainfall within 12 hours. Tephra was applied in September 2005 and samples extracted after 18 months in March 2007. Peat blocks, approximately 150mm-deep, were cut out encompassing the sampling ring and approximately 20mm beyond that ring. Blocks were wrapped in plastic and stored upright. A number of the marker rings were lost between application of the tephra and sampling, reducing the total number of samples to 33. Several of the rings had become totally overgrown by moss in the intervening period.

In the laboratory, the blocks were sub-sampled into 10mm-deep slices and sub-samples dried at 110º C. Samples were incinerated at 550°C to remove organic material. For the coarser tephra (>0.5mm) the tephra particles could be separated from the ashed debris using an appropriate sized sieve and then weighed. For the finer tephra samples were prepared by acid washing following Pilcher and Hall (1992) as described above. These samples were examined under the microscope to confirm presence or absence of tephra. The concentration estimates obtained by the *Lycopodium* method are only a semi-quantitative indication of tephra concentration. As tephra loads were high and we wished to investigate tephra loss from the experimental system tephra weights were determined by calculating the loss on ignition deviation from adjacent tephra-free peat.

To investigate the movement of tephra over a longer time-scale a core was extracted from one of the plots on the Moss of Achnacree, Scotland (grid reference NM9134) subject to experimental tephra deposition in 2002 (Payne & Blackford 2005a&b). A 30cm core was removed with a Russian-pattern corer from plot 8 in April 2008, almost six years after initial application. The core was sub-sampled and tephra concentration enumerated as for the rainfall simulation experiments.

A further stage of the experiments was designed to study the impact of microtopography and site wetness on the vertical movement of tephra. A sequence of ten sampling sites was established along a 90cm transect spanning the water table gradient from a hollow (depth to water table (DWT): 0cm at time of sampling) to a hummock (DWT: 13cm, Table 2) on a small *Sphagnum*-dominated poor fen at Cwmffynnon, North Wales (UK grid reference SH6556). 20g of tephra was applied within plastic rings (as for Whixall) in August 2007. Coarse tephra in the size range 2-3.35mm was used for practical simplicity. Monolith blocks were removed after 3.5months in December 2007. Blocks were sub-sampled and tephra extracted as for the Whixall experiments.

The final stage of the experiments was to investigate the lateral movement of tephra once deposited on the surface of peatlands. These experiments were carried out on three contrasting peatlands: Miller Moss, a *Sphagnum*-dominated blanket mire in north Cumbria (UK grid reference NY3033); Featherbed Moss, a degraded, *Eriophorum*-dominated Penine blanket mire (UK grid reference SK0992) and Moidach More, a raised bog in Morayshire, Scotland (UK grid reference NJ0241)(Fig. 2). 30g of Őraefajökull tephra sieved at 150µm was placed on a hard surface on a hummock. A series of glass slides were smeared with petroleum jelly and placed along a downwind transect. Experiments were conducted on windy days; there was some overnight rain during the experiments on Miller Moss and Featherbed Moss. Slides were collected after 24 hours. 22x22mm coverslips were placed over the slides, scanned under the microscope at 400X magnification and the total number of tephra shards counted.

RESULTS

Rainfall simulation experiments

During rainfall simulation tephra particles very rapidly (within an hour) began to stick together to form a cohesive layer at the peat surface. This layer was continuous with the 0.5cm thick application. With the 1mm thick application the tephra appeared to be concentrated into small patches across the surface. Some tephra appeared to be moved to the sides of the boxes and may have moved down the edges of the peat blocks. There was also some indication of impact on plants with discoloration of *Sphagnum* under the thicker applications.

Tephra profiles show a very rapid decline in concentrations with depth with the vast majority of tephra maintained at the surface (Fig. 3). Replicate profiles from the same blocks generally show very similar patterns. Maximum shard penetration varied from 4 cm (experiment RFS2b-2) to 14cm (RFS1b-1 and RFS1b-2). There is no indication of any impact of rainfall intensity on the distance tephra penetrates. Tephra penetrates further in experiments RFS1a and RFS1b with less intense rainfall. There is also no clear indication that tephra shards are found further below the surface with a thicker application. Under lighter rainfall, tephra was found deeper with the thicker layer in RFS1b than RFS1a, but the reverse was found under heavier rainfall with tephra found marginally deeper in RFS2a than RFS2b.

Whixall field experiments

Concentration profiles for the Whixall sites are shown in Fig. 4. In only 8 of the plots is the highest tephra concentration found in the uppermost sample. The tephra peak is up to 5cm below the surface in some plots. In all but two cases the tephra peak coincides exactly with the position of the bog surface at the time of application. The exceptions are Plot 33 and Plot 4 in which the tephra peak is 1cm below the surface at time of application. The concentration profile for plot 4 is complex with high tephra concentrations over a 5cm deep section of the profile. Generally, although most shards are retained near the former surface, some penetrate a considerable depth. In all but one plot with tephra <1mm some tephra was found in samples through the whole length of the monolith suggesting these blocks do not include the full distribution. In the majority of cases the concentration profile is a simple monomodal distribution with most tephra retained in a single peak at the former peat surface. However, there are some exceptions to this. Several profiles contain minor secondary peaks such as those observed in Plots 23, 24 and 28. In most cases these represent comparatively small differences in tephra concentration, potentially due to minor discrepancies of sampling or enumeration, and can be considered unimportant. In Plots 2 and 9 there are more distinct secondary peaks and in plots 4 and 10 the tephra peak is spread over several centimetres suggesting a more serious taphonomic issue.

Concentration profiles show both a downward limb with tephra penetrating below the depth of application and an upward limb with tephra moving into the peat subsequently accumulated. Results provide some indication of a general relationship between the depth tephra penetrates and the tephra particle size (Fig. 5). The coarsest tephras (>2mm) are generally retained towards the surface of the peat while fine tephra may penetrate the entire length of the peat block. A full assessment is difficult as the monolith blocks do not include the full length of the concentration profile for the finer tephras. There is also some indication of a relationship between the particle size of tephra applied and the proportion of that tephra recovered during sampling (Fig. 6). Recovery rates vary considerably and are as low as 29% in one plot (19) where the enclosing ring had become displaced. Recovery rate is much lower with fine tephra layers (<300μm) than with coarser layers (>0.5mm). To a large extent this may be due to the inevitable higher errors in calculating tephra concentration on the basis of the known loss-on-ignition of the peat rather than by direct measurement. This is shown for instance by Plot 23 which has a recovery rate calculated as 110%. However it is unlikely that the limitations of the methodological approach are sufficient alone to account for recovery rates below 50% as shown for some plots. There is also an indication of some difference in the distance tephra penetrates between sampling areas, with tephra apparently penetrating consistently further in area 1 (Fig. 7). However interpretation of these results is complicated both due to tephra penetration beyond the monoliths and the loss of some experiments from some areas. So, for instance, several of the plots with coarser tephra were lost from area 2.

Moss of Achnacree experiment

Fig. 8 shows the tephra concentration profile from plot 8 of the Moss of Achnacree site in April 2008. The tephra peak was found in the sample from 2-3cm with shard penetration to 6cm. The depth of the tephra peak and maximum shard penetration do not exceed that found in many of the Whixall plots despite the much-longer period of study, this is probably due to lower accumulation rates in this site.

Cwmffynnon Field experiments

To investigate if differences between sampling areas are due to differences in wetness an additional experiment was carried out applying tephra across the water table gradient from a pool to a hollow. Tephra penetrates from 3 to 6cm (Fig. 9). In all cases the vast majority of tephra is contained within the uppermost sample at the surface of the peat with concentrations declining very steeply with depth. There is no indication that tephra penetrates below the depth of the monolith and recovery rates are high (mean=96%). The more limited tephra movement in this experiment compared to the Whixall study is attributable to the shorter-period and coarse tephra. Unlike the Whixall experiments none of the layers had become overgrown. There is no simple relationship between the depth of tephra penetration and the wetness of the site (Fig. 10). The maximum tephra penetration in these plots is found with an intermediate depth to water table, but the overall variability is small.

It is conceivable that some of the vertical movement of tephra observed in the field experiments was due to displacement in sample extraction, transport, storage and sub-sampling but we do not believe this is likely to be significant. The Cwmffynnon experiments were removed when the peat was frozen so disturbance during sampling can be excluded as an explanation for these results at least.

Experiments on lateral movement of tephra

The experiments on Whixall Moss noted a low recovery rate of fine tephra (<300μm). This might relate to the methodology used, but it is not clear if this is enough to account for the scale of loss. One possibility is that tephra is lost by airbourne transport across the mire surface. To investigate this, further experiments were conducted. Results are shown in Fig. 11. In all three sites tephra movement appears very limited, with tephra moving a maximum of 1m in Featherbed Moss and Moidach More, and 3m in Miller Moss. In all cases, the proportion of tephra which moves at all is very small.

DISCUSSION

The extent of tephra movement

These experiments show some tephra may move a considerable distance down through the peat but in the vast majority of cases most tephra remains trapped at the surface. These experiments therefore support the suggestion that a peak in tephra concentration provides an isochron which records the position of the peat surface at the moment of deposition. The two instances where tephra peak concentration did not coincide with the position of the surface at the time of deposition showed only a 1cm displacement. The reasons for this are not clear from the visible nature of the sampling plots. This small discrepancy is unlikely to be important once the peat is compressed as it enters the catotelm.

The maximum depth that tephra may reach varies between experiments. Tephra penetrated through the entire 150mm length of many of the Whixall profiles. It is quite likely that some tephra moved at least 200mm in these plots. Tephra moved up to 6cm in the Cwmffynnon and Moss of Achnacree experiments and up to 14cm in the rainfall simulation experiments. There are probably several causes of these differences including the differing lengths of the experiment, quantity of tephra applied, size of the tephra particles, differences in the peat composition and structure and environmental conditions. These distributions would be considerably reduced with plant decay and compression as the peat enters the catotelm. Nevertheless, over 150mm of surface peat still represents many years of accumulation. Initial work on spheroidal carbonaceous particles elsewhere in the Whixall site suggests that 150mm of peat might represent 70-100 years of peat accumulation (Parkinson 2007). A pine stump at 55-57cm gave a radiocarbon date of 2307±110 BP (Turner 1964). The rapid tephra movement shown by the rainfall simulation experiment suggests that most of the vertical movement of tephra down through surface peat occurs very shortly after deposition, this was also suggested by one of the experiments of Payne et al. (2005).

The field experiments focused on lateral movement show that once tephra reaches the surface of a peatland it is unlikely to move any great distance across the surface. The wet and complex surface of peatlands appears to be very effective at trapping and retaining tephra. The rainfall simulation experiments suggest that there is a tendency for tephra to 'clump' into patches on the peat surface. Although a mechanism for this process is unclear it may provide an explanation for the fine-scale variability of tephra layers seen in the field.

Controls on tephra movement

The Whixall experiment provides some indication that finer tephra may penetrate deeper into the peat. However, the inadequate length of the monoliths makes this difficult to assess for the tephra particle sizes which are most relevant to the stratigraphic record. Particle-size dependent movement is potentially important as it may provide a means to locate the isochron in complex concentration profiles such as that shown in Fig. 1C. To investigate this further the tephra particle sizes through this tephra profile were investigated. For each sample 50 tephra shards were measured along their longest axis using a graticule at 400X magnification. Fig. 12 shows average tephra particle size. Results show there is a clear tephra size peak at 39-41cm. If this size peak is taken to show the position of the surface at the time of deposition this suggests that the concentration peak at 37-38cm does not accurately record the position of the isochron and that significant upward migration of tephra shards has occurred. Further work will be required to establish whether tephra particle size provides a good indication of isochron position.

There is no indication from these results that the extent of tephra movement depends on the wetness of the site. It remains possible that there is some relationship with wetness but this is probably indirect through differences in peat density and porosity. It is notable that tephra penetrated considerably further in the Whixall experiments than the previous Moss of Achnacree experiments, despite the shorter period of time. The Moss of

Achnacree has been subject to some drainage and has relatively dense and humified surface peat compared to the loose *Sphagnum* typical of the Whixall site.

An issue not investigated in these experiments is the density of the tephra. It is possible that denser, less vesicular shards may be liable to sink further through the peat.

Complexity of tephra profiles

These results do not provide any direct explanation for why some tephra profiles are complex. This may well depend on the fine details of peat morphology. Thin sections examined by Payne et al. (2005) suggested that tephra might follow 'channels' in the peat. In Whixall Plot 3 it was noted that tephra appeared to have penetrated an unconformity in the peat surface between two patches of different moss species leading to the relatively extended vertical distribution of tephra in this site. It seems probable that such fine-scale variability in peat structure is a major cause of the differences between concentration profiles.

Upwards translocation of tephra

The Whixall and Moss of Achnacree experiments have succeeded in reproducing both the downwards penetration of tephra below its position of application and the upwards penetration of tephra into subsequently accumulated peat. Downward penetration of tephra is unsurprising with tephra shards sinking through gaps in the peat and being moved by the percolation of meteoric water down through the acrotelm. The upward 'tail' of declining tephra concentrations above the isochron is harder to explain. Some of the pattern may be due to the sampling resolution; if the full thickness of the visible layer is not caught by a single sample then there will inevitably appear to be a decline in concentrations above. However these results show a more significant tail than could be explained by this alone. We suggest three possible mechanisms for the upward 'tail' of tephra commonly noted in tephrostratigraphic studies from peatlands:

1) Secondary deposition. Tephra may be moved onto the mire surface from the surrounding area.

2) Movement of tephra with a rising water table. Clymo and MacKay (1987) show that pollen may be moved vertically through *Sphagnum* by the rising and falling of the water table. It is possible that tephra could be moved from the isochron into higher sediments on a rising water table.
3) Plant growth. Tephra may be moved upwards by plant growth through the tephra layer.

Of these possible mechanisms secondary deposition cannot explain the pattern seen in these experimental plots. Although it is possible that some tephra may have moved between plots the lateral distribution experiments suggest that tephra movement across the surface of an (unfrozen) peatland is likely to be limited. Secondary deposition may be significant in some field situations where tephra deposited in the area surrounding the peatland is not adequately trapped and is available to be redeposited. However the upward tail of tephra concentrations found in some sequences may represent several hundred years of peat accumulation. It seems unlikely that unconsolidated tephra deposits persist for such a long time, particularly with cryptotephras where the quantity of tephra deposited is extremely small.

Movement of tephra on a rising water table may be a tenable hypothesis for the upward tail of tephra concentrations observed here. The higher density and angular morphology of tephra particles would suggest that this process must be much less effective than for the pollen grains studied by Clymo and MacKay (1987). It is conceivable that this mechanism might account for why tephra in positions of intermediate wetness moved furthest in the Cwmffynnon experiment.

Movement of tephra with plant growth is also plausible although most of these plots are dominated by *Sphagnum* which due to its growth pattern is not thought to lead to significant disturbance of peat stratigraphy. Overall we suggest that water table movement and plant growth are probably the most important vectors for the upwards displacement of tephra in peatlands.

Limitations of the experiments

The scope of this study is inevitably limited. All our sites were in the UK and are mostly ombrotrophic. Processes may be quite different in other peatlands with different vegetation, fauna and climatic conditions. In fens receiving significant minerotrophic water input the mechanisms of tephra layer formation may be much more complex with many of the problematic processes previously described from lake sediments. In wooded peatlands it is possible that trapping of tephra by vegetation will be greater with it taking longer for tephra to reach the peat surface.

CONCLUSIONS

In practical terms these experiments show that it is essential for tephrostratigraphic studies in peatlands to construct (and publish) concentration profiles. In most cases the concentration profile will be simple and the concentration peak can be taken to represent the palaeo-surface. If the concentration profile is complex then the isochron must be treated with caution. Tephra size might provide a guide to help resolve the position of the isochron in these cases but further work will be needed to confirm this.

In most cases the taphonomy of tephra seems to be relatively simple in ombrotrophic peatlands, at least when compared to situations such as lakes where there may be numerous issues. However, this is not a cause for complacency as there is evidence that tephra taphonomy in peatlands can sometimes be less straightforward. A number of mechanisms can be theorised which might serve to lead to post-depositional movement of tephra, these are detailed in Table 3. Mechanisms vary from the probable such as movement by plant growth to the unlikely or infrequent such as disturbance of the peat by bog bursts or tree fall. Problems may be particularly acute in peatlands which are frozen for much of the year giving more scope for lateral movement of tephra, particularly when incorporated in drifting snow (Bergman *et al.* 2004). Cryoturbation may disrupt tephra layers contained within the peat, potentially leading to secondary deposition. Tephra taphonomy is a topic which requires detailed consideration in all studies which attempt to use tephrochronology as a dating method in peatlands, and particularly in high-resolution studies.

This study further demonstrates the value of an experimental approach in Quaternary Science. Attempts to understand the taphonomy of tephra based on the stratigraphic record have been undermined by issues such as the potential for multiple geochemically-indistinguishable tephras (eg. Pyne-O'Donnell 2008). Experiments allow multiple simulations with the ability to control for external factors and vary conditions at will. Experimental modern-analogues provide a powerful approach to resolve many practical questions in Quaternary Science.

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FIGURES and TABLES

Figure 1. Examples of tephra concentration profiles from sites in southern Alaska (Payne and Blackford 2004; Payne et al. 2008).

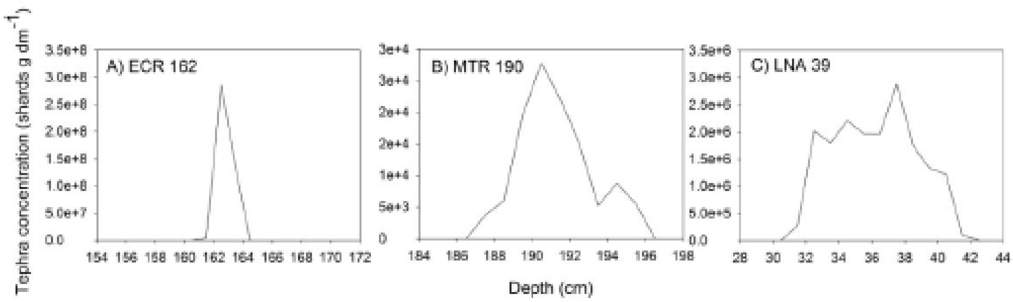

Figure 2. Location map of field sites referred to in this paper.

Figure 3. Tephra profiles from eight locations within four rainfall simulation experiments: RFS1a, RFS1b, RFS2a and RFS2b. Experiments RFS1a and RFS2a had a 1mm thick tephra layer applied, experiments RFS1b and RFS2b had a 05mm thick tephra

layer applied. Experiments RFS1a and RFS1b were subjected to rainfall at 12 mm $hour^{-1}$, experiments RFS1b and RFS2b were subjected to rainfall at 26 mm $hour^{-1}$.

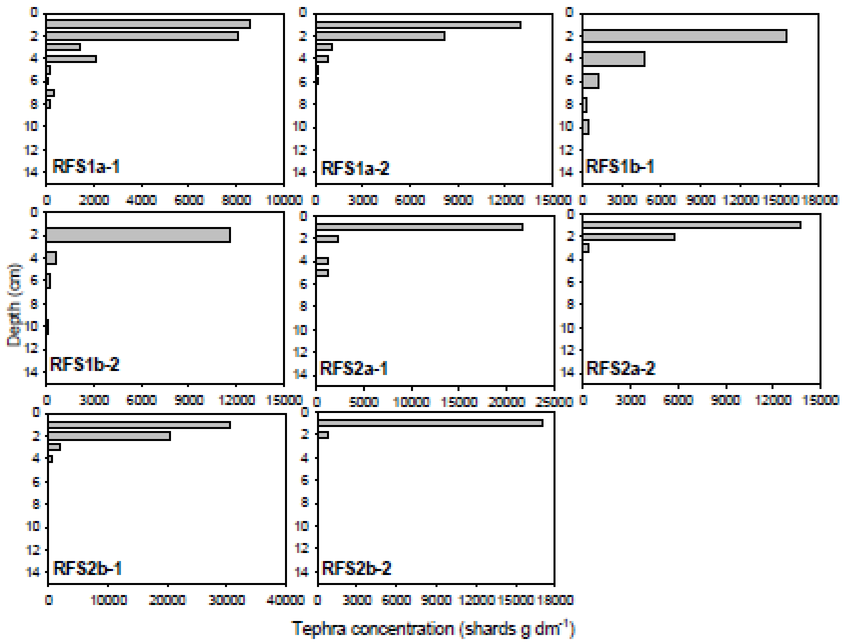

Figure 4. Tephra profiles from field experiments at Whixall Moss. See Table 1 for experimental scenarios and vegetation of the plots.

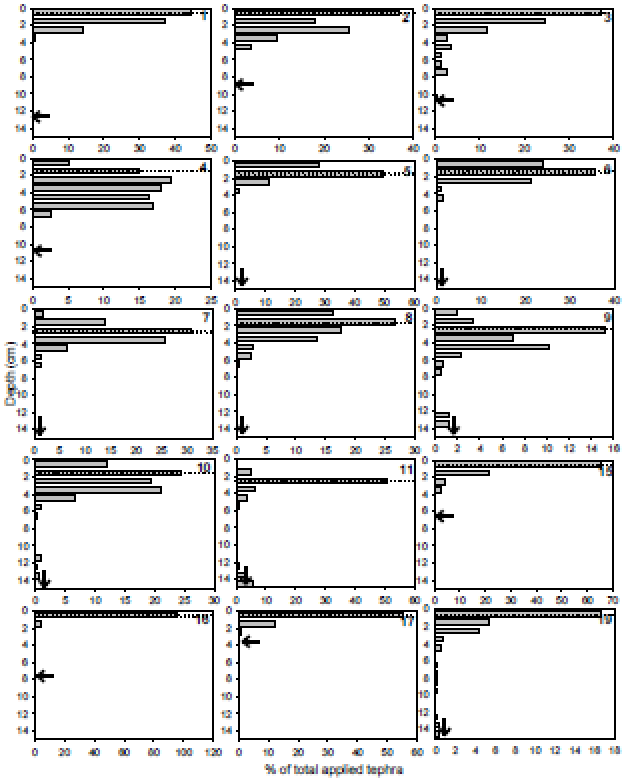

Figure 5. Distance penetrated by tephra against tephra particle size for Whixall experiments.

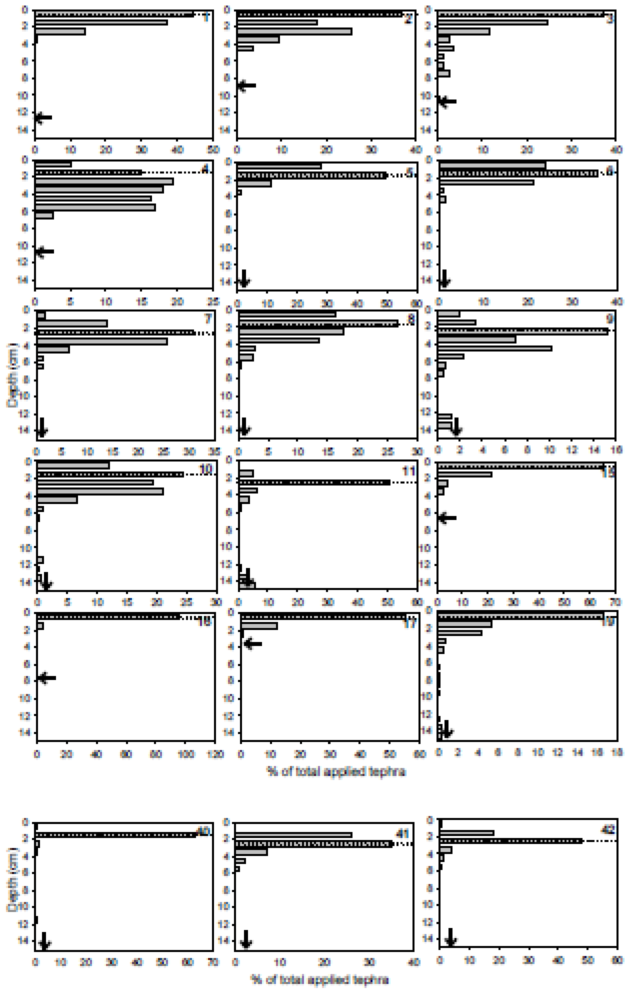

Figure 6. Tephra yield against tephra particle size for Whixall experiments.

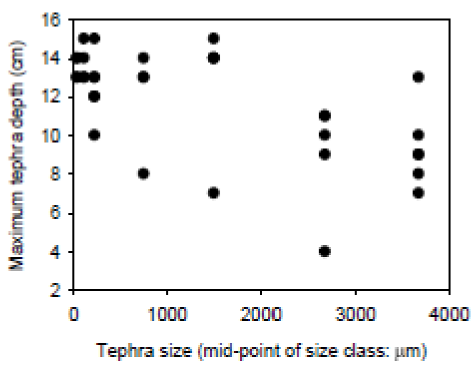

Fig. 6

Figure 7. Maximum tephra penetration depth by sampling area for the Whixall site.

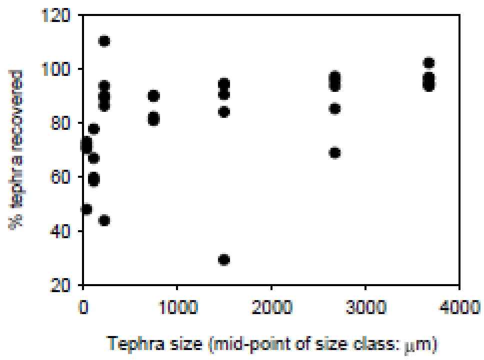

Figure 8. Tephra profile from experimental plot MAC 8 in April 2008. Plot was subject to 200 gm^{-2} of <300μm tephra in May 2002.

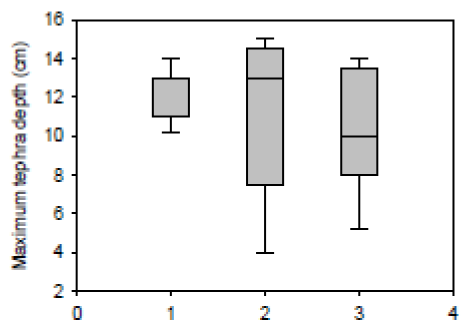

Figure 9. Tephra profiles from field experiments at Cwmffynnon. See Table 2 for experimental scenarios and vegetation of the plots.

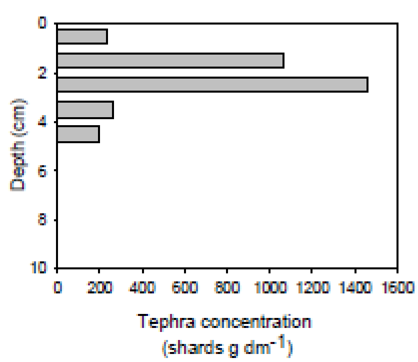

Fig 9

Figure 10. Maximum tephra penetration depth against depth to water table for Cwmffynnon experiments.

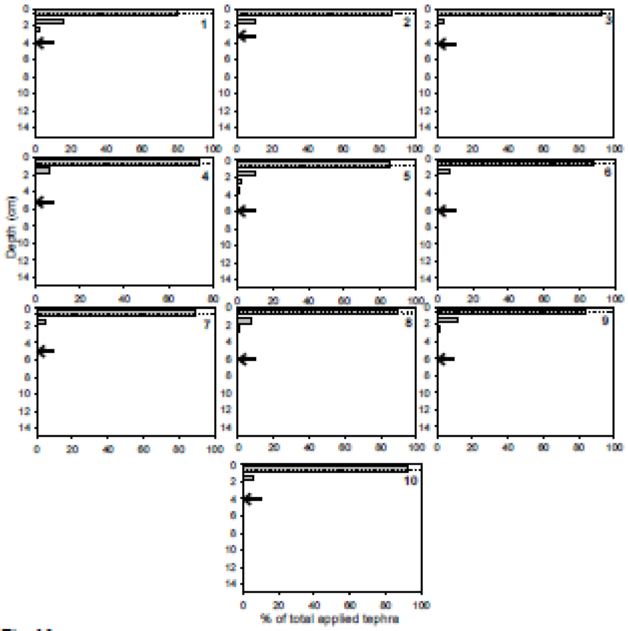

Fig. 10

Figure 11. Lateral movement of tephra in three sites. Plots show total number of shards found under a 22x22 mm coverslip at increasing distance downwind from tephra placed on a hard surface.

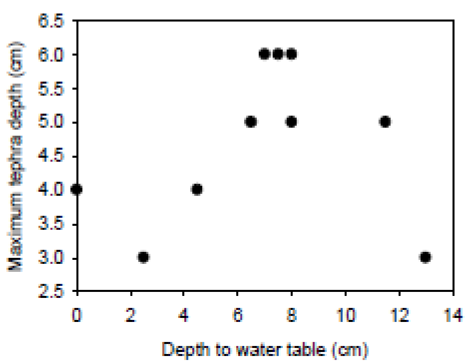

Fig. 11

Figure 12. Tephra concentration and particle size for LNA 39 tephra (see Figure 1).

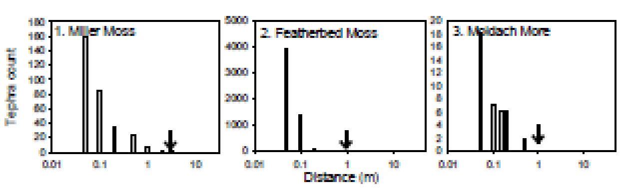

Table 1. Experimental treatments and vegetation of Whixall plots. Only experiments which were recovered at the end of the period are included here.

Table 2. Experiments applied to the Cwmffynnon field site, showing depth to water table and vegetation of the sampling spots. .

Table 3. Possible mechanisms of tephra movement in peatlands and an assessment of their probability. .

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Table 1.

No.	Area	Application	Vegetation
1	1	50g 3.35-4mm	*Sphagnum* sp., *Polytrichum commune*
2	1	50g 3.35-4mm	*Sphagnum* sp., *Erica tetralix, Vaccinium oxycoccus*
3	1	50g 2-3.35mm	*Sphagnum* sp., *Erica tetralix, Polytrichum commune, Eriophorum vaginatum*
4	1	50g 2-3.35mm	*Sphagnum* sp., *Erica tetralix*
5	1	50g 1-2mm	*Sphagnum* sp., *Erica tetralix, Empetrum nigrum*
6	1	50g 1-2mm	*Sphagnum* sp., *Vaccinium oxycoccus*
7	1	50g 0.5-1mm	*Sphagnum* sp., *Erica tetralix*
8	1	50g 0.5-1mm	*Sphagnum* sp., *Erica tetralix, Polytrichum commune, Vaccinium oxycoccus*
9	1	10g 150-300µm	*Sphagnum* sp., *Vaccinium oxycoccus*
10	1	10g 150-300µm	*Sphagnum* sp., *Erica tetralix, Vaccinium oxycoccus*
11	1	2g 75-150µm	*Sphagnum* sp., *Polytrichum commune, Eriophorum vaginatum*
15	2	50g 3.35-4mm	*Sphagnum* sp., *Eriophorum vaginatum, Vaccinium oxycoccus*
16	2	50g 3.35-4mm	*Sphagnum* sp., *Eriophorum vaginatum, Vaccinium oxycoccus*
17	2	50g 2-3.35mm	*Sphagnum* sp., *Eriophorum vaginatum, Vaccinium oxycoccus, Erica tetralix*
19	2	50g 1-2mm	*Sphagnum* sp., *Eriophorum vaginatum, Empetrum nigrum, Erica tetralix, Calluna vulgaris*
23	2	10g 150-300µm	*Sphagnum* sp., *Eriophorum vaginatum, Vaccinium oxycoccus, Andromeda polifolia, Calluna vulgaris, Erica tetralix*
24	2	10g 150-300µm	*Sphagnum* sp., *Vaccinium oxycoccus, Eriophorum vaginatum*
25	2	2g 75-150µm	*Sphagnum* sp., *Vaccinium oxycoccus, Eriophorum vaginatum*
27	2	10g <75µm	*Calluna vulgaris, Sphagnum* sp., *Vaccinium oxycoccus*
28	2	10g <75µm	*Sphagnum* sp., *Eriophorum vaginatum, Vaccinium oxycoccus*
29	3	50g 3.35-4mm	*Sphagnum* sp., *Eriophorum vaginatum, Vaccinium oxycoccus*
30	3	50g 3.35-4mm	*Sphagnum* sp., *Eriophorum vaginatum, Vaccinium oxycoccus, Andromeda polifolia*
32	3	50g 2-3.35mm	*Sphagnum* sp., *Eriophorum vaginatum, Vaccinium oxycoccus*
33	3	50g 1-2mm	*Sphagnum* sp., *Eriophorum vaginatum, Vaccinium oxycoccus*
34	3	50g 1-2mm	*Sphagnum* sp., *Vaccinium oxycoccus*
35	3	50g 0.5-1mm	*Sphagnum* sp., *Eriophorum vaginatum, Vaccinium oxycoccus*
36	3	50g 0.5-1mm	*Sphagnum* sp., *Eriophorum vaginatum, Vaccinium oxycoccus, Andromeda polifolia*
37	3	10g 150-300µm	*Sphagnum* sp., *Vaccinium oxycoccus, Erica tetralix*
38	3	10g 150-300µm	*Sphagnum* sp., *Vaccinium oxycoccus, Eriophorum vaginatum*
39	3	2g 75-150µm	*Sphagnum* sp., *Vaccinium oxycoccus, Eriophorum vaginatum*

40	3	2g 75-150µm	*Sphagnum* sp., *Vaccinium oxycoccus, Eriophorum vaginatum, Andromeda polifolia*
41	3	10g <75µm	*Sphagnum* sp., *Vaccinium oxycoccus, Eriophorum vaginatum, Drosera rotundifolia*
42	3	10g <75µm	*Sphagnum* sp., *Vaccinium oxycoccus, Eriophorum vaginatum, Drosera rotundifolia*

Table 2.

No.	Distance from start of transect (cm)	Depth to Water Table (cm)	Vegetation
1	0	0	*Eriophorum, Carex*
2	10	2.5	*Carex, Eriophorum, Sphagnum* sp.
3	20	4.5	*Carex, Eriophorum, Sphagnum* sp.
4	30	6.5	*Carex, Sphagnum* sp.*, Drosera rotundifolia, Erica tetralix*
5	40	7	*Sphagnum* sp.*, Eriophorum*
6	50	7.5	*Sphagnum* sp.*, Eriophorum, Erica tetralix*
7	60	8	*Sphagnum* sp.*, Eriophorum, Erica tetralix*
8	70	8	*Sphagnum* sp.*, Drosera rotundifolia, Erica tetralix, Eriophorum*
9	80	11.5	*Sphagnum* sp.*, Erica tetralix, Eriophorum*
10	90	13	*Sphagnum* sp.*, Erica tetralix, Eriophorum*

Table 3.

Processes	**Mechanism**	**Likelihood**
Gravitational sinking	Tephra particles sinking down through voids in the peat.	Probable
Vegetation growth	Tephra moved down through the peat by root penetration, or up by shoot growth.	Probable.
Rainfall percolation	Tephra carried down through peat by water flow and the impact of rain drops.	Probable
Lateral water flow	Tephra carried across peatland by lateral water movement.	Probably limited in bogs, possibly more important in fens.
Water table variability	Tephra moved up and down through the peat with the rise and fall of the water table.	Probable
Wind action	Movement of tephra across the peat surface with wind. Likely to be exacerbated if surface is frozen.	Probably limited importance, at least in temperate peatlands.
Cryoturbation	Disruption of tephra layers by frost action.	Probable in high latitude peatlands.
Snow drifting	Redistribution of tephra across a peat surface with drifting snow and accumulation in hollows.	Probable in high latitude peatlands.
Bioturbation	Tephra moved by microfauna within the peat. Perhaps also by trampling of peat by larger animals.	Probably limited importance.
Secondary deposition	Tephra may be transported by wind or water from unconsolidated deposits in areas surrounding the peatland	Uncertain.
Erosion, Bog burst, Peat cutting, Fire, Tree fall, Earthquakes	Disturbance of peat potentially leading to remobilization of buried tephra.	Possible but rare.